Applications of Carbon Nanotubes for Human Space Exploration

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Abstract

An ongoing project at NASA/Johnson Space Center (JSC) provides a detailed examination into the properties, characterization, and applications of single-walled carbon nanotubes (SWNTs) for use in future human spaceflight. Nanotubes are of vital interest due to their outstanding strength-to-weight ratio, which is an order of magnitude higher than today's structural materials. Replacing current vehicle structural members with nanotube composite materials could greatly reduce the mass of next-generation spacecraft. Preliminary experiments in fabrication and testing of composites reinforced with carbon nanotubes indicate improvements in mechanical properties. Production of SWNTs at JSC allows for these experimental studies to be performed to verify theoretical predictions. Further areas of interest at JSC involving nanotubes are in nanoelectronics and hydrogen storage. The size of electrical components and equipment will be greatly reduced by using electrically conductive SWNTs.

Background

Since the discovery of carbon nanotubes by Iijima in 1991[1], NASA has become increasingly interested in taking advantage of their extraordinary properties[2,3,4]. These multi-walled nanotubes provided a fascinating structure, but each one was uniquely fabricated, with no consistency of form and shape. Once a method for producing single-walled tubes was established by Smalley's group at Rice University[5], labs could produce small quantities of nanotubes which appeared to be basically defect-free. This double laser ablation method has proven to routinely provide fairly small amounts of single wall carbon nanotubes for basic and applied research. The electric arc process for nanotubes[6] has also begun to provide a useful supply of single wall nanotubes for those who have been able to imitate and improve the initial process. These and other methods[7,8] are now being investigated by many groups to find a way of making large quantities of nanotubes to meet the demand worldwide. A major obstacle to the growth of nanotube applications has been the lack of nanotube availability to research organizations. Therefore, it is important to study how and why nanotubes are formed so that reasonable attempts can be made to scale up current efforts.

Although a number of attempts have been made to reinforce polymers with carbon nanotubes[9,10,11], these efforts have mostly been minor due to high cost and the lack of available nanotubes in the marketplace. The high inherent strength of nanotubes shows great promise for the possibility of this type of nanocomposite. The structure of the nanotubes themselves is believed to relate to the ability of a composite to utilize the

Proceedings of NanoSpace '98

mechanical strength of the nanotubes. That means that nanotubes with greater numbers of defects should not provide as high a tensile strength as the more perfect single wall nanotubes. However, many other aspects also factor into the ability to transfer the high mechanical strength to the composite. Interfacial bonding between the fiber and matrix may be most important in determining the nanocomposite's strength, and this may require chemical functionalization or activation of the reinforcement. Because of the numerous trials which must be attempted to optimize these materials, only some beginning steps have been made to try to take advantage of the inherent strength of carbon nanotubes. A concerted effort must be sustained in this area to quicken the pace of development of nanocomposites.

NASA's interest in nanotubes has grown rapidly since their discovery early this decade because of the properties evident in nanoscale materials. Mechanical, electrical, and thermal properties of these one-dimensional fibers can be advantageous, along with their extremely high surface area. Single wall carbon nanotubes can be electrically conductive, leading to nanoscale electrical wiring and components. This could not only shrink today's microchips, but could allow a much higher volume of information to be computed on-orbit. Recent reports of ballistic conductance in nanotubes[12] are especially interesting for electron transport, and NASA is closely monitoring this area to determine how to best push this into application development. Utilization of this wide range of properties can lead to many applications such as high strength materials, flat panel displays, nanoelectronics and nanodevices, and a whole range of other possibilities using nanotubes as templates to make other nanoscopic materials. It is believed that the nanotechnology field will lead to smaller and more lightweight components for next generation spacecraft.

Nanoscale phenomena are not new in the field of materials science. Atomic level interactions have been studied for years. What makes nanotechnology different is the use of the material in its nanoscopic form instead of using nano-phenomena to enhance the properties of a macroscopic material. These may be the first steps in making true molecular devices, as evidenced in early molecular level experiments in nanoscale gears. By helping to push the field of nanotechnology, NASA is prepared to take advantage of advances in nanoscale applications as they become available.

Nanotube Production at Johnson Space Center

Johnson Space Center has embraced the field of nanotechnology through a joint effort with Rice University for production and applications of single wall carbon nanotubes (SWNTs). Early in 1997 JSC quickly set up a nanotube production facility based on the double laser ablation method pioneered by Smalley's group at Rice[5]. This provides SWNTs for use in applications studies at JSC and elsewhere. Figure 1 shows a typical SEM photograph of SWNTs produced at JSC. A major goal of the project is to study the production process in order to attempt to develop bulk methods for making nanotubes. It is believed that a study of this type is prerequisite to scaling up any process for commercial production. It will be difficult at best to produce large quantities of high quality SWNTs without a firm grasp of the mechanisms of formation.

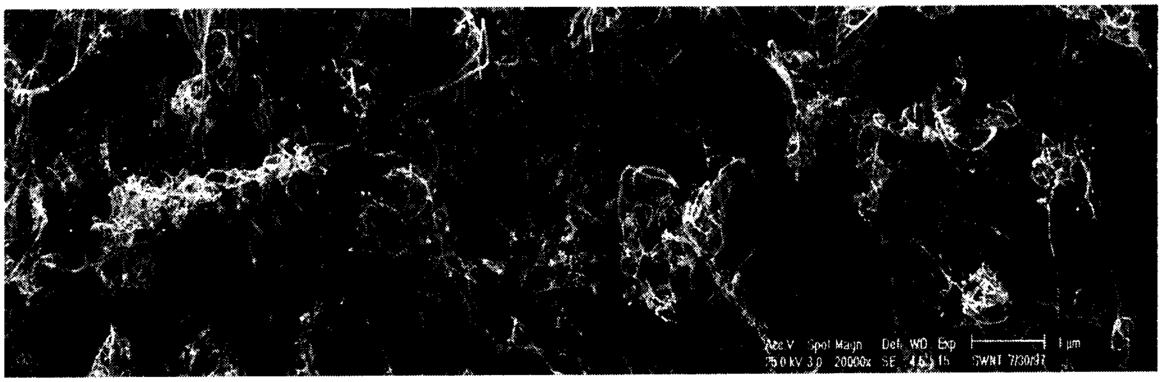

Figure 1. As-produced single wall carbon nanotube material made at JSC using the laser ablation method

Members of the JSC nanotube team have concentrated efforts on a diagnostic study of the laser ablation method for producing nanotubes. This parametric study of the variables in the setup has revealed the data presented by Carl Scott and Sivaram Arepalli at this conference[13]. By looking at the plasma plume formed in the furnace, measurements using an intensified charge coupled device allows spectral analysis of the C_2 Swan bands. This information can be obtained spatially along the flow tube and also with time. Therefore, the intensity at various positions and times can be compared for process optimization. Perhaps this gathering of data will lead to enhanced production methods for nanotubes, whether it be using laser ablation or another method using the same type of growth mechanisms. While continuing the spectral work, the diagnostics area has been expanded to include laser induced fluorescence for mapping out ground state C_2 and C_3 along with the nickel and cobalt catalysts. Addition of this data may provide enough insight to finally settle the question of how nanotubes are produced and to scale up production.

Nanotube purification has been shown to be important, due to the amount of amorphous carbon produced in nanotube soot. Also, the nickel and cobalt catalysts must be removed so that a pure sample of nanotubes can be available for applications studies. By following the Rice University process for nanotube purification[14], we have been able to rid the raw material of the undesired species. Figure 2 shows a typical sample of SWNT after the purification process. This method involves a nitric acid reflux followed by a filtration step. In this system some nanotubes may be lost, especially if their structure includes defects. However, after this process the SWNT material is pure enough to be used for property evaluation such as use in high strength composites.

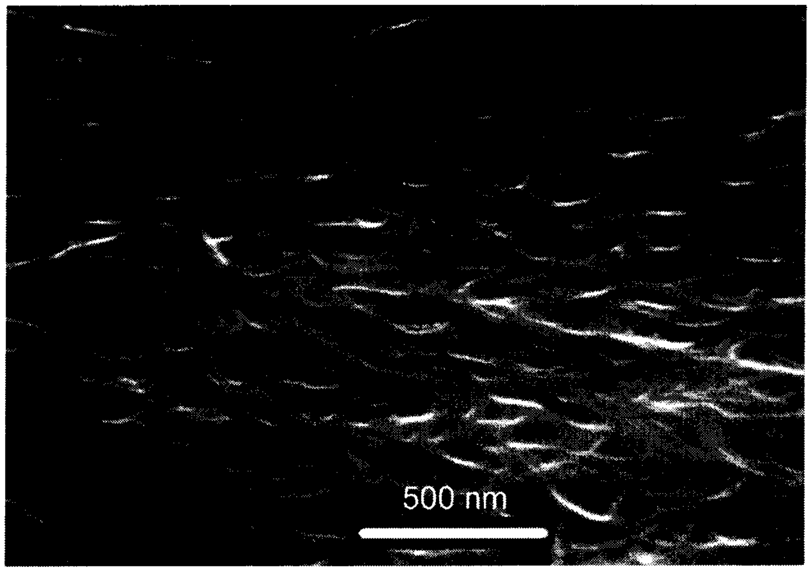

Figure 2. Sample of SWNT material after purification process at JSC.

Nanotube Composites

Although initial forays have previously been made in the area of nanotube composites, there has not been much progress in the evaluation of the interaction between matrix and reinforcement phases. Most studies have involved the use of multi-walled nanotubes (MWNT), and it is believed that SWNT will have some different interface characteristics with both polymers and metals. Because of the more ideal nature of SWNT when compared to MWNT, research at JSC has focused on these composites using SWNT bundles.

A number of studies have taken place at JSC including wetting, bonding, and tensile strength enhancement. Efforts have been concentrated in the area of reinforcement of thermosetting polymers with SWNT reinforcement. Due to the lack of bulk methods of nanotube production, test specimens were scaled down to a size which could be reinforced with up to 8 wt% fibers. Although it is thought to be important, initial evaluations have not included functionalizing the nanotubes or attempting alignment along the tensile axis.

SWNT were mixed into a matrix of epoxy (Tactix 1-2-3, Ciba Specialty Chemicals) and then cast in a stainless steel mold to make small dogbones, scaled down in size from ASTM-638. Mixing was initially done manually to determine whether other methods would be necessary for homogeneous fiber dispersion. The mold with uncured epoxy was placed in a vacuum chamber to lower the specimen porosity, which proved to be especially important in the reinforced system. Curing was complete after a cycle of one hour at 120°C and then two hours at 177°C. Final specimen size was approximately 17 mm long and had a 3 mm wide gage section. Fiber loading range was 0-8 wt%, with high volume fractions becoming increasingly difficult to mix manually.

Early composite samples had high amounts of porosity, but these problems were overcome through better preparation methods. Examination of the fracture surface using a Phillips XL40 FEG-SEM shows the dispersion and attachment of nanotubes as shown in Figure 3. This portion of the surface is in the fast fracture region where many rough epoxy edges are apparent. This allows a close look at places where nanotubes attach to the epoxy. SWNT in the as-produced condition tend to form bundles of nanotubes held together by Van der Waals forces. One observation of the composite samples is that the ends of the nanotube bundles tend to be forked as they enter the epoxy. Also, it is obvious that there is a directionality to the nanotubes in the photograph, as if they have all been laid down onto the surface, perhaps by gravity after fracture occurred. Material in Figure 4 has been loaded with fewer nanotubes, thus making the individual bundles easier to examine. In this photograph there are a number of bundles which are forked as they enter the matrix and are stretched taut between two fracture planes in the epoxy. This is an important observation because it is shown that both ends of the bundles are still attached to the matrix due to interfacial bonding. However, the amount of force transferred across this interface is still unknown.

With very small polymer specimens such as these, tensile testing proved to be quite difficult, as expected. Not only did small off-axis loading greatly affect the strength results due to addition of bending forces, but minor flaws in the specimen are believed to have also had a serious detrimental effect because of early crack initiation. Therefore, results from this preliminary set of tests were inconclusive as to whether the nanotubes increased the strength of the tensile samples. In specimens which were more highly loaded with SWNT, it became difficult to get fracture in the gage section as opposed to fracture of the grip. This may lead to the conclusion that the gage section was strengthened by the nanotubes and made the grip too weak for the additional strength. Further testing with larger specimens is now underway.

Future work on nanotube composites will continue the efforts described here and will include testing of larger samples, advanced mixing methods, use of purified SWNT, functionalization of the nanotubes, and evaluation of a number of polymer systems. In the area of thermoplastic polymer systems, JSC is working with Enrique Barrera's group at Rice University to develop nanotube composites. One use of some specific thermoplastic systems which is of interest to NASA is in rapid prototyping. Development of stronger materials than currently available is essential if this method is to be used for functional prototypes and possible replacement parts. In addition, other systems and processing methods involving metal matrices are also of general interest. However, the obstacles to making strong metal composites are thought to be more complex with the current base of knowledge of nanotubes and their interaction with metal alloys.

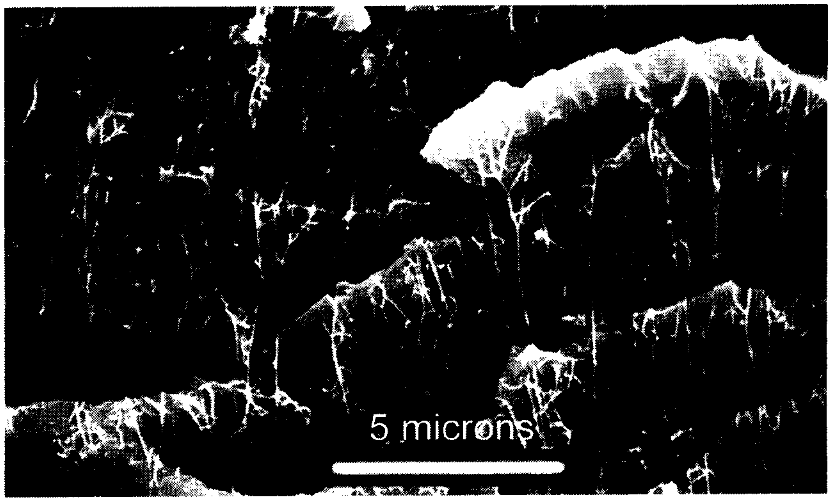

Figure 3. SWNT bundles dispersed in epoxy matrix, showing forked ends and favorable bonding characteristics. Ends of bundles are still attached to epoxy after fracture.

Figure 4. SWNT bundles in epoxy at lower reinforcement percentage, showing taut bundles still attached to matrix.

Other applications

Applications of nanotechnology for NASA are too numerous to list, as it is acknowledged that uses of molecular technology will be wide-ranging in the coming decades. Other types of nanomaterials also will become a normal part of future projects due to promising properties which are inherent with nanoscale objects. However, the current experimental focus at JSC is in the area of single-wall carbon nanotubes, which already have been shown to be quite useful for applications using their strength, electrical properties, and small size.

In the materials field, not only are composites important, but macroscopically long nanotube fibers are also of interest. One can imagine ropes, webbings, and fabrics made of this incredibly strong material. A few unique applications for NASA would be in the areas of inflatable space habitats, advanced spacesuits, and orbital debris protection.

Nanoelectronics shows more and more promise with recent work in molecular transistors and ballistic conductance. With today's microchips shrinking down to nanochips in the future, much more data reduction and calculation may be done inside a spacecraft. This could prove especially important as missions extend farther from Earth, requiring longer times for data transmission. Information processing will be more time intensive as spacecraft become more advanced, and more computing power will be necessary. This type of reduction of size will be required so that information may be processed in a reasonable period of time on orbit. Carbon nanotubes may be the breakthrough necessary to make this computing a reality.

Electron emission through carbon nanotubes may make high brightness flat panel displays a reality, along with other similar applications. Use of nanotubes as electron emitters will provide a number of advanced technologies of importance for NASA missions. Another topic of importance is energy storage, due to the large surface area for low amounts of mass of nanotubes. The nanotubes may be either used by themselves or as templates for other materials to make other nanoscale materials for use in power storage devices. Current efforts using nanotubes as starting materials for batteries and ultracapacitors show good signs. A number of claims have been made for using nanotubes for storing hydrogen for fuel cells and other applications. If this or a similar technology proves reliable, NASA would like to use it to store hydrogen for long duration missions.

Conclusions

Johnson Space Center has made a commitment to pursue and push high payoff technologies for human operations in space, with the goal of furthering exploration of the solar system[15]. One area of current pursuit involves the single wall carbon nanotube initiative, including working toward bulk nanotube production methods and applications for nanotubes. JSC is pursuing better production methods by attempting to understand nanotube formation in the plasma plume. If modeling of nanotube strength properties turns out to be a reality, and those properties can be implemented into actual materials, NASA will be ready to commit to fabricating nanotube composites for future space vehicles. NASA is already deeply involved in nanotechnology, and it is widely accepted that molecular devices and nanoscopic materials and electronics will be important to exploration goals.

Acknowledgements

Thanks go to the JSC nanotube project team and especially to Lubert Leger for his leadership in setting up the program. Also, much appreciation is due for Richard Smalley and Andrew Rinzler at Rice University in providing the collaboration for the JSC laser ablation process. Other JSC team members to be thanked include Sivaram Arepalli, Carl Scott, William Holmes, Jeremy Jacobs, Joe Victor, Beatrice Santos, Charles Hakes, Lawrence Lewis, and Thomas Leimkuehler.

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